11. Computer simulation of aortic valve geometry

11.1. Background

The local geometry of the aortic valve plays an important role in its performance. In the past, different factors influencing aortic valve configuration have been the focus of many studies. The coaptation area and effective height \((h_E)\) of the cusps have been identified as important parameters in determining the immediate and long-term functioning of repaired aortic valves [1-3]. Aortic aneurysms have been found to reduce cusp coaptation, initiate aortic insufficiency, and increase cusp stress [4, 5], a mechanism which seems to be caused by dilatation of the sinutubular and/or aortoventricular junction (AVJ).

In valve-sparing aortic replacement procedures, the aortic root is replaced by a graft while retaining its native aortic valve. The disadvantages of these techniques, however, lie in the risk of reduced valve durability due to non-physiologic opening and closing performance, leading to incomplete restitution of normal valve configuration [6].

Since there are no available data regarding which valve repair configuration yields the least amount of cusp stress, parametric numerical models are needed to match the graft to the patient’s pathology. Various numerical models have been used to study the effect of root geometries on the mechanical performance of tricuspid aortic valves, with and without aortic sinuses [7-9] and aneurysmatic roots [4, 11] for valve-sparing procedures [4, 10, 11]. In dry models [4, 7, 10, 11] it has been suggested that the sinuses are important for minimising cusp stress. Ranga et al. [8] and Katayama et al. [9] used fluid structure interaction (FSI) models to study different types of aortic roots. These models did not include contact modelling between the cusps, a factor that plays a critical role in aortic valve diastolic behaviour, especially for valve-sparing procedures [12]. Marom et al. employed FSI models of compliant cusps and roots [13] to determine the influence of changes in AVJ diameter on the geometry and mechanics of the cusps [14].

11.2. Methods

Three-dimensional geometry of a normal aortic valve and root was reconstructed with a base configuration of a healthy valve. Nine additional initial geometries, with geometric heights \((gh)\) between 15.4 and 18.9 mm and with an AVJ diameter \((d_{AVJ})\) between 20 and 30 mm, were also modeled. The healthy case had a \(d_{AVJ}\) of 24 mm and \(gh\) of 16.2 mm. In all the models with different cusp sizes the root dimensions were identical and equal to the base case with a \(d_{AVJ}\) of 24 mm. Two straight rigid tubes were added upstream and downstream to move the flow boundary conditions away from the regions of interest. Isotropic and linear elastic material properties were assumed in the current model [14]. The flow was assumed to be laminar and the blood to be slightly compressible and Newtonian [14]. Full Navier-Stokes equations were used to model the flow, while force and momentum equilibrium equations were solved for the structure using a finite element code [19]. The \(h_E\)s were calculated from no-flow (“dry”) static models, similar to the clinical measurements, while the other parameters were calculated from fully compliant FSI models [14]. The mesh of the structural and flow parts were chosen following a mesh refinement study [13]. The FSI model was solved by a partitioned solver with non-conformal meshes [14].

11.3. Effect of aortoventricular junction on cusp configuration and stress

Projected two-dimensional deformed valve configurations with different AVJ sizes, as calculated from the FSI models, are presented in Figure 11.1. The \(h_E\) was calculated from dry models when the applied pressure load fully closed the valve. The left column in Figure 11.2 plots \(h_E\) as a function of \(d_{AVJ}\). As hypothesised, the \(h_E\) decreased while the \(d_{AVJ}\) increased, and is in the normal adult range [2]. Coaptation was calculated from the FSI models. The partially-opened valves \((d_{AVJ})\) of 28 and 30 mm) were prolapsed into the left ventricle and showed a “belly region” in the cusps. Figure 11.1 and the right column in Figure 11.2 show that the coaptation height \((h_C)\) increases while the \(d_{AVJ}\) decreases. The average \(h_C\) in Figure 11.2 is defined as the coaptation area divided by the free-edge length. The mechanical cusp stresses were also calculated...
from the FSI models. The largest stress values for all cases were found on the free-edge near the commissures. Stress in the partially-open valves ($d_{AVJ} = 28$ mm and $30$ mm) was higher than in the fully-closed valves, while the model with $d_{AVJ}$ equal to $24$ mm showed the lowest stress. The highest stress was found in the $28$ mm case, probably due to the prolapse of the valve or the contact pressure that acts on a smaller coaptation area. The lowest stress was found in the "healthy" case with a $d_{AVJ}$ of $24$ mm.

**Figure 11.1:** Projected deformed configurations of the closed valves with different $d_{AVJ}$. The cases of $28$ mm and $30$ mm are not closed even though this view does not disclose this fact.

11.4. Effect of geometric height on cusp configuration and stress

Similar to the previous section, the projected two-dimensional configurations of the valves with different gh are presented in Figure 11.3. The left column in Figure 11.4 plots $h_E$ as a function of gh and shows that $h_E$ increases with the increase of the gh. Figure 11.3 and the right column in Figure 11.4 show that the $h_C$ increases with the increase of the gh. The case with the smallest gh was not fully closed and, similar to the previous section, all the closed valves have smaller stresses. The healthy case in this parametric study also has the lowest mechanical stress.

11.5. Clinical implications

In order to prevent regurgitation, it is considered desirable to have the valves completely closed with a relatively large coaptation area. It was found that increasing the $d_{AVJ}$ results in reduced average $h_C$ (Figure 11.2). This theory appears plausible and is consistent with other valve preserving surgical procedures [15] and recent observations in aortic valve repair [16]. The second parametric study shows that the average $h_C$ increases with the size of the cusp. While these results also seem plausible, it is not common practice to change the gh of the cusps during valve repair procedures. Nevertheless, the $h_E$ can be easily measured in the clinical setting and both of these parametric studies indicate that there is a correlation between the $h_E$ and the average $h_C$. Figure 11.5 shows the relationship between the average $h_E$ and $h_C$ in all the ten models of the two parametric studies. All three cases with an $h_E < 9$ mm had partially-opened valves during diastole. This is in accord with the findings of Bierbach et al. [2], who used transthoracic echo-cardiography measurements to demonstrate that 96% of all patients with moderate or more severe aortic insufficiency had an $h_E < 9$ mm. Therefore, improving $h_E$ during valve repair or replacement could also lead to increased coaptation and better...
performance, especially for non-prolapsed valve geometries. The observations in this model indicate that focused reduction of $d_{AVJ}$ alone may increase $h_C$ and thus normalise cusp configuration. Further studies should be performed to investigate whether highly focused intervention at the $d_{AVJ}$ could achieve the same results in a clinical setting.

Figure 11.5: The average coaptation height ($h_C$) as a function of the effective height ($h_E$).

Another metric for closure quality could be the maximum principal stress, since excessive stress values could damage the valve and reduce its durability [17]. In both of the above parametric studies, the partially-open valves with an $h_C<9$ mm had larger stress distribution probably resulting in lower durability. Those cases of $d_{AVJ}$ between 22 and 26 mm and those of $h_E$ larger than 16 mm are preferable, since they have stress less than 500 kPa, which represents a level of stress where tissue stiffening could develop [18]. Therefore, the case with “healthy” dimensions has the best combination of coaptation and low mechanical stress.

References

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